A Dual-Radio Contention-Based Protocol for Paired Spectrum Access and TV White Space

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***Abstract*—Spectrum regulation for cellular networks, last-mile wireless broadband access, but also for the new secondary usage of the TV white space, often favor a paired radio spectrum so that different frequency channels are used for down- and uplink (base vs. mobile devices). This setup is also referred to as frequency division duplex. However, such a setup makes it difficult to apply contention-based protocols like those standardized by IEEE 802.11, because they were designed so that downlink and uplink share the same frequency channel. Yet the simplicity of the 802.11 protocol and its decentralized operation make it attractive for smart grid and consumer electronics applications using TV white space or licensed spectrum. Therefore we investigate a contention-based 802.11-like protocol for paired spectrum. We leverage its downlink-uplink separation into a protocol design that combines contention-based distributed medium access with a managed reaction to packet collisions. We also demonstrate why this paired spectrum approach is relevant and desirable for TV white space secondary spectrum access. The main advantages of this protocol are (1) enabling the usage of simple and low cost contention-based 802.11-like devices in paired spectrum, (2) providing collision detection management in the uplink, and (3) an inherent resource reservation for downlink traffic. The evaluation results confirm the validity of the proposed protocol design and demonstrate the benefits obtained from collision detection management.**

I. INTRODUCTION

The past years have witnessed an extensive proliferation of Wi-Fi IEEE 802.11 protocols as a standard for wireless technology and devices. The simple and low-cost nature of the 802.11 contention-based Medium Access Control (MAC) protocol is one of the reasons for its wide acceptance. However, a traditional 802.11 protocol is built to operate in an environment where downlink and uplink use the same radio spectrum [1]. In contrast, many of today's radio systems are regulated (or opportunistically search spectrum holes) in a way that requires a separation of downlink and uplink frequencies. Therefore such systems cannot directly use the distributed protocol approach of the traditional 802.11 approach.

Examples of radio systems that rely mainly on paired spectrum are cellular networks such as Long Term Evolution (LTE) and mobile WiMAX [2]. Another prominent example of a system that gains from paired spectrum approaches is the newly released TV White Space (TVWS) [3], [4].

For those cases where spectrum holes are detected by cognitive radios, it can be the case that the spectrum holes found by base station and mobile devices do in fact not overlap on the same frequency channel. A traditional listen-before-talk 801.11 protocol, however, requires all devices to operate on the same frequency. As a result, for the most frequently encountered real world scenarios, such a protocol does not allow communication because there is no common channel available for transmitters and receivers to exchange packets – even though base stations and mobile devices have found their own frequency holes that could allow them to transmit separately. Therefore, in such situations, a protocol that can handle the separation of uplink and downlink is needed. Such a protocol then allows a base station and mobile devices to transmit on different frequencies.

In the present paper, we propose an 802.11-like Carrier Sense Multiple Access (CSMA) protocol that is intended to operate in paired spectrum. Inspired by the idea of Collision Avoidance (CA) in this context (usually refered to as CSMA/CA - the key idea is that a node is not allowed to transmit if it determines that another node is already transmitting), we describe a protocol that includes Collision Detection (CD). A first draft approach for a paired spectrum protocol was proposed in [4]–[6]. With the protocol discussed in the following, base station and mobile devices could communicate using an 802.11-like technique in paired spectrum, as opposed to not being able to communicate at all using traditional 802.11. On top of the classic CSMA/CA technology, we take advantage of an additional channel in paired spectrum to integrate collision detection into the proposed protocol. This property reduces the time wasted by colliding packets and therefore increases system throughput.

Several protocols have been advanced to deal with the problems caused by paird spectrum; Protocols such as GSM, IS-95, UMTS, WiMAX and LTE are the usual choice for cellular networks [7], [8]. However, these protocols are complex and centralized. The protocol proposed in this paper aims at serving as a complimentary low-cost and simple non-centralized random access alternative to these protocols. 802.11 devices are widely deployed nowadays because of their simplicity. By extending the existing and successful 802.11 protocol towards paired spectrum usage, we want to design a protocol that inherits from the 802.11 protocol the advantages of simple contention-based protocols. Therefore, the protocol discussed here could find potential usage in low cost cognitive radio scenario and in future cellular networks.

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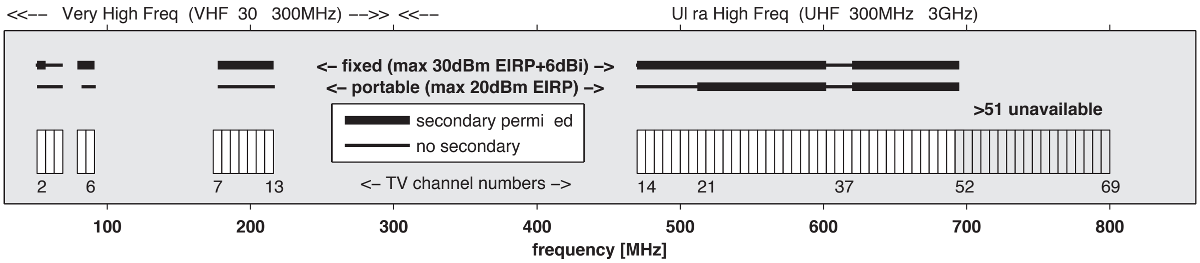


Fig. 1. Ground rules imposed by TVWS regulation. TV channels 2-69 that might be used by TVWS devices are indicated as white blocks. Solid lines above the channel blocks illustrate the permissions for secondary usage of TV channels for fixed and portable devices. A thin line indicates that the respective TV channel is excluded from secondary TVWS usage. Channels 52-69 will be used for next generation cellular and public safety applications in the future.

In the following sections, we investigate the relationship between the throughput of the system and the number of users and discuss the impact of collision detection and different modulation and coding schemes. We show that the proposed protocol has high throughput in downlink. We will further illustrate that the protocol's throughput in the uplink is comparable to traditional 802.11.

II. RELATED WORK

A short summary of related work is provided in the following. A lot of attention has been focussing on cognitive radio networks and TVWS. In [9], early work that highlights that adequate spectrum is available to provide new broadband opportunities is discussed. In [10], the fundamental and critical importance of economic investment considerations is shown by considering the status of rural versus urban areas. In [11], an efficient sensing algorithm evaluating the energy and feature detection was proposed. More recently, several practical systems were developed that improved the state-of-art. In [12], a novel system that allows high-throughput wideband nodes to co-exist with unknown narrowband devices is described and used for real-life testbed evaluations. This technology cannot be used over white spaces because the U.S. regulator, the Federal Communications Commission (FCC), does not allow testing the presence of an incumbent primary system by active probing with a transmission, which is a main characteristic of the system of [12]. Another novel system was discussed in [13]. The design and implementation of this system was presented based on a technique, which reduces the time to detect transmissions in variable channel bandwidth systems by analyzing raw signals in the time domain. In [13], the client was designed following a traditional Wi-Fi access point discovery by scanning each channel and listening for periodic beacons from APs on the same channel.

III. TVWS REGULATION

The FCC radio regulator of the U.S. describes in its public report "Unlicensed Operation in the TV Broadcast Bands" [3] a first regulatory framework for TVWS, which serves as base for this paper. The FCC defines two classes of TV White Space Device (TVWDs): fixed TVWDs and personal/portable TVWDs. The personal/portable TVWDs operate either under control of a fixed TVWD or autonomously. Different regulatory rules are defined for the two different device classes. One important rule is a geolocation database for the usage by primary services, and the requirement for checking this database periodically.

The TVWS includes the very high frequency (VHF) and the ultra high frequency (UHF) channels. VHF includes channels 2-13 in the frequency spectrum at $54 \ldots 72\,\text{MHz}$ and $76 \ldots 88\,\text{MHz}$, and a third block of frequency at around $200\,\text{MHz}$. Figure 1 illustrates the main aspects of TVWS spectrum regulation.

The UHF channels 14-20 can be found at $470 \ldots 512\,\text{MHz}$, UHF channels 21-36 at $512 \ldots 608\,\text{MHz}$, and UHF channels 37-51 at $608 \ldots 698\,\text{MHz}$. The frequency separation between UHF channels $4\,\&\,5$ is $4\,\text{MHz}$, the separation between UHF channels $6\,\&\,7$ is $86\,\text{MHz}$, and the separation between UHF channels $13\,\&\,14$ is $254\,\text{MHz}$. Fixed TVWDs are permitted to operate in the VHF channels except channels $3\,\&\,4$, and on the UHF channels, except channels 36-38. The reason for the exclusion of channels $3\,\&\,4$ is to prevent interference with external devices that are often connected with shielded cables to a TV utilizing these channels. The reason for exclusion of channels 36-38 is to prevent interference with radio astronomy measurements at channel 37.

The operation of portable TVWDs is even more restricted because of their potentially nomadic mobility pattern. Portable TVWDs are only permitted to operate in the UHF channels starting from channel 21, with the exception of channel 37. Portable devices are not permitted on channels below 21. since in thirteen metropolitan areas of the U.S. some of those channels are used for public safety applications. In Figure 1, two horizontal lines summarize if secondary usage is permitted for a given channel, for fixed and for portable devices. Exclusions are indicated by thin instead of solid thick lines. Similar TVWS spectrum usage rules are under discussion for other regulatory domains such as Europe. In the FCC rules, there are many more important regulatory requirements such as power levels, antenna gains, the use of a central database for spectrum management, and reservations for protection of Part 74 wireless microphones. All these aspects are not directly relevant to this discussion, which focusses on the benefits of downlink-uplink separation.

A venue such as an entertainment event or a festival can be registered and protected against any secondary TVWS activity. Instead of relying on geolocation with GPS or similar means, for fixed TVWDs, a "professional installer" [3] can configure the device location during setup. Further, fixed TVWDs must transmit their identities and location information to facilitate their identification in case of unwanted interferences. Devices are permitted to operate on an adjacent TV channel with the maximum allowed transmission power of $+16\,\text{dBm}$ ($4\,\text{dB}$ lower than on non-adjacent channels), i.e. $40\,\text{mW}$).

IV. DOWNLINK-UPLINK SEPARATION

Figure 2 illustrates the actual TVWS availability of TV channels for three example locations in the US. The data (channel availability) for this figure were collected in March 2010, using a set of public tools [14] [15] [16]. We see that many channels are already allocated by primary services (TV broadcast). In densely populated areas like Market Street, San Francisco (top line) or Wall Street, New York (bottom line), only a small number of TVWS channels are available. Where channels are available for secondary usage, they rarely are available for fixed and portable usage together (base and mobile devices). Hence, a separation of uplink and downlink dual channels will be useful. At the third location, Walt Disney World, Orlando we observe a few free channels. Because of the radio regulation, none of them would be available for fixed and portable secondary spectrum usage together. The FCC regulations for TVWS require three consecutive unused channels for downlink transmissions. This rule limits the usage of TVWS to channel 9 only [3]. Furthermore, channel 9 is not available for uplink traffic from mobile devices (referred to as "portable" in [3]) in this location because only higher channels are allocated to mobile devices by FCC. As result, again the separation of downlink and uplink may provide benefits.

An example of the European Conference of Postal and Telecommunications Administrations (CEPT) [2] regulation for LTE is shown in Figure 3. It can be seen that much of the cellular spectrum around $800\,\text{MHz}$ is regulated in a way that implies downlink and uplink separation.

V. PROTOCOL DESIGN

The 802.11-like Carrier Sense Multiple Access (CSMA) protocol operating in paired spectrum is described in this section.

A. Operation in Paired Spectrum

The basic operation of the proposed protocol in paired spectrum is shown in Figure 4. We assume there is only one base station – the traditional base station – and multiple mobile devices - the traditional mobile devices. Each device (both base and mobile) is operating on two different radio frequencies simultaneously - one for uplink, one for downlink. Downlink means that the base station is allowed to transmit Data/ACK to mobile devices. Uplink means that the mobile devices are allowed transmitting Data/ACK to the base station. At the same time, the base station is permitted to listen to/receive on the uplink, because receiving radio signals does not generate interference. The same setup applies to mobile devices, which are permitted to listen to/receive on the downlink spectrum.

The uplink utilized by mobile devices uses an 802.11-like CSMA/CA contention control protocol. A device with a new packet to transmit monitors the physical medium continuously. If the medium is idle for a period of time that equals the Distributed Inter Frame Space (DIFS), the device will initialize a back-off counter and start to count down (collision avoidance). At the time when the back-off counter reaches zero, the device is allowed to transmit. In the case when another transmission has taken place from other devices before the back-off counter reaches zero, the back-off counter freezes, the device waits until it senses another idle DIFS duration on the physical media, and resumes counting down at the end of the idle DIFS interval. Otherwise, i.e., if the channel is sensed busy (either at the start of sensing or during the DIFS), the device persists to monitor the channel until it senses an idle interval of DIFS duration. The choice of the back-off counter is the same as in the traditional 802.11 protocol, which adopts an exponential back-off scheme. After each sensed DIFS, the back-off counter is uniformly chosen from the rage $(0, w-1)$, where w is called the Contention Window (CW). The value w depends on the number of unsuccessful transmissions of the packet. At the first transmission attempt, w is set equal to CW_{min}. After each unsuccessful transmission attempt, w is doubled, up to a maximum value $CW_{max} = 2^m CW_{min}$, where m is the maximum back-off stage a packet can take. The values of CW_{min} and CW_{max} are specified in the standard, and they are physical medium specific. To ensure that a packet indeed gets through, a positive acknowledgment (ACK) is transmitted back from the destination to signal the source a successful packet reception. The ACK is immediately transmitted back at the end of the packet after a time period that equals the Short Inter Frame Space (SIFS). As the SIFS interval is shorter than the DIFS interval, no other device can transmit until the destination has transmitted the ACK signal. If the transmitter does not receive the ACK within a predefined time period, or if the transmitter detects a new packet transmission on the channel, the transmitter reschedules a packet retransmission [1] [17]. The uplink protocol is the same as the basic two-way DATA/ACK mechanism of the traditional 802.11 protocol. The four-way handshaking RTS/CTS access mechanism can be easily included.

B. Exploiting the Benefits of Paired Spectrum

The Collision Avoidance (CA) technique employed by the traditional 802.11 listen-before-talk protocol may reduce the chance of transmission collisions in the uplink, but such collision are still possible. Frames inevitably collide when devices choose to initiate packet exchanges at (about) the same time. When such a collision happens, in the absence of a feedback channel, two devices with colliding frames still transmit the entire frames without realizing the collision. Then, after the transmissions, these devices wait for the acknowledgment. The devices realize that a collision has happened only when the

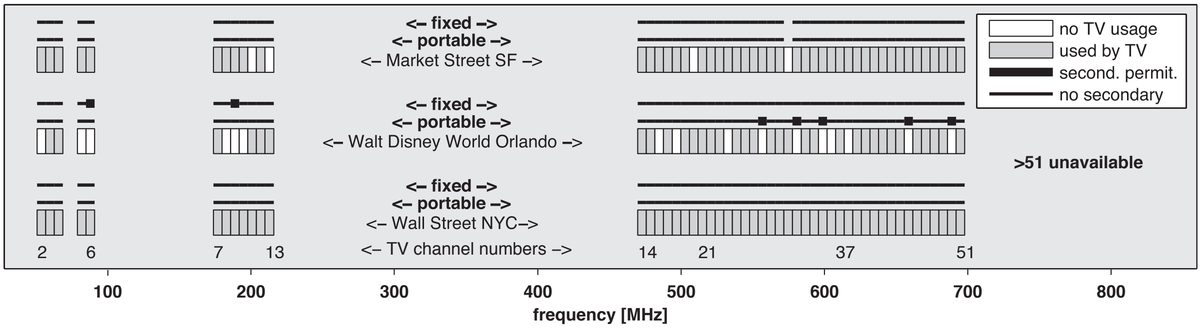


Fig. 2. Example TVWS availability. In densely populated areas, only a limited number of TVWS channels are available. Orlando observes a few free channels, but none of them would be available for fixed and portable secondary spectrum usage together.

acknowledgments are not received (because they were never sent back). With paired spectrum, however, a feedback channel from the base station to the mobile devices exists even during intervals when the mobile devices are transmitting. A use of this channel requires full duplex communication capabilities at the devices, and this feature is assumed for all devices throughout this paper. We further assume that the base station can detect that packets arrive from multiple devices at the same time (collision detection).

When the base station detects collisions, it can request immediate interruption of the current transmission via the downlink, as illustrated in Figure 4 by transmitting a CD notification. All stations suspend useless transmissions upon receiving this notification. Such a collision detection technique can reduce significantly the average time a channel is occupied by the transmission of colliding frames. Although this uplink collision detection technique enables a potential performance improvement, collision detection cannot fully eliminate the usage of an ACK. In addition to problems at the receiving device (that may cause the loss of a packet), detection of a collision by the base station depends on the instantaneous channel condition.

C. On the Feasibility of Collision Detection (CD)

The Ethernet 802.3 contention-based CSMA protocol makes use of collision detection and so-called jamming signals for notifying transmitters about collisions. This approach is possible because at typical Ethernet distances, wires do not significantly attenuate signal strengths. Transmitted signals are received at nearly the same power level across a wire. However, in wireless, contention-based systems such as 802.11, a CSMA protocol cannot detect collisions immediately because the wireless medium strongly attenuates a signal with increasing distance. In wireless scenarios, collisions happen at the destination, not necessarily at the location of a transmitter, a consequence of the hidden device (hidden terminal) problem. Multiple colliding frames transmitted at the same time by mobile devices and received by the base station interfere with each other. They together trigger the carrier sensing of the base station, but the preamble synchronization as part of frame reception will fail (ignoring capture effects). Therefore, one simple way to realize a collision detection in our setup is a simple noise detection, together with an unsuccessful preamble detection. If downlink and uplink use the same channel, a receiving base station cannot notify any transmitting mobile devices about collisions in the uplink. However, with dual channels and downlink-uplink separation, the base station as the intended receiver of multiple colliding frames can transmit the optional notification signal upon receiving either a jammed preamble or noise.

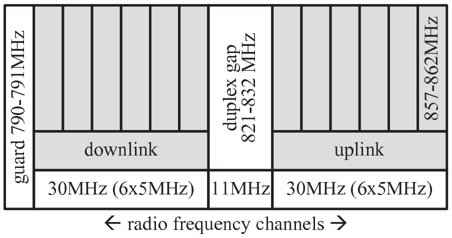


Fig. 3. CEPT regulation for Long Term Evolution (LTE) at 800 MHz. Much of the cellular spectrum is separated into downlink and uplink: For example, LTE operates in paired spectrum, as indicated here for the spectrum around 800 MHz [2].

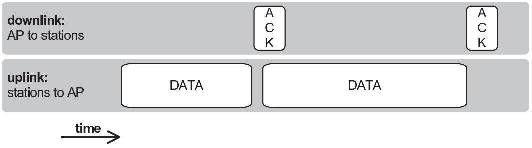
D. Dual-Radio for Full Duplex

The potential drawback of the proposed downlink-uplink separation is that a full duplex scheme requires two independent radios at the mobile devices. This requirement might result in increased power consumption and cost/complexity. However, other existing protocols also gain from dual radio solutions, e.g., multi-hop mesh. See earlier work that discusses the benefits of dual-radios in infrastructure-assisted multi-hop scenarios with hidden stations, [18]–[20].

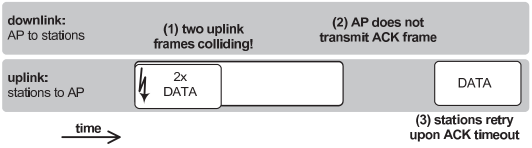
VI. RESULTS AND VALIDATION

We now illustrate the feasibility of the proposed protocol with results from stochastic simulation, based on extensive simulation campaigns using a modified version of the wireless system emulator Jemula802 [21]. The tool Jemula802 was developed as an open source software that includes the module Jemula as kernel for event-driven stochastic simulation. The original software models the IEEE 802.11 standard. For this work, it has been modified to model the proposed protocol.

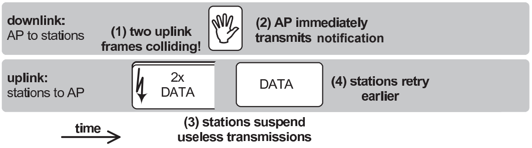
(a) Downlink frame exchanges. In full-duplex systems, devices can transmit and receive at the same time. ACKs are transmitted in parallel to DATA frames, at the same time.



(b) Uplink transmissions. Again, with full-duplex, ACKs and DATA frames are transmitted at the same time.



(c) Uplink DATA frame collision and ACK timeout.



(d) Uplink collision with detection and notification.

Fig. 4. Basic operation of the proposed protocol working in paired spectrum.

The simulation environment is first used to measure the system saturation throughput - all devices always have data to transmit (saturation). In system setup, the number of base stations is set to be one, and the number of mobile devices varies from 1 to 100. A number of 100 associated devices per access points seems unrealistically high for today's Wi-Fi hotspots. In contrast to today's Wi-Fi, TVWS targets much larger coverage areas with a potentially larger number of devices per access point. For this reason, such high numbers are included in this evaluation. We assume downlink and uplink are 20 MHz each. The parameters used are summarized in Table I, with protocol parameters closely following the traditional 802.11a/g protocol [1] for 20 MHz Orthogonal Frequency Division Multiplex (OFDM). We realize that for applications like typical LTE spectrum and TVWS instead a channel bandwidth of 2x5 MHz is used. However, there also exists an OFDM physical layer definition for 802.11 5 MHz, originally discussed in 802.11j and now part of proprietary 5 MHz solutions [1]. After adjusting the parameters used in Table I to be compatible with 5 MHz (or other bandwidth), the following qualitative analysis is still valid and a similar trend in the results is observed. In this simulation campaign, results with payload size equals 2304 byte are shown. Similar trends are observed in the simulations for other packet sizes.

TABLE I
SIMULATION PARAMETERS.

uplink parameters	*value*	*downlink parameters*	*value*
Bandwidth [MHz]	20	Bandwidth [MHz]	20
OFDM Symbol [μs]	4	OFDM Symbol [μs]	4
PLCP Preamble [μs]	16	PLCP Preamble [μs]	16
PLCP Header [μs]	4	PLCP Header [μs]	4
Payload [$byte$]	2304	Payload [$byte$]	2304
Slot Time [μs]	9	Slot Time [μs]	9
SIFS [μs]	16	MAChdrSTOP [$byte$]	10
DIFS [μs]	34		
CW_{min}	16		
CW_{max}	128		

Simulation results are visualized in Figures 5-7. In each of the figures, the horizontal axis represents the number of mobile devices, and the vertical axis represents the system throughput. Figure 5 depicts the system saturation throughput when the optional uplink collision detection is switched off while Figure 6 illustrates the results when collision detection is switched on. Figure 7 compares the previous two scenarios on the same scale. Each figure contains results with three different modulation and coding schemes as defined in the 802.11 standard [1] - 64QAM3/4 (54 Mb/s), 16QAM1/2 (24 Mb/s) and BPSK1/2 (6 Mb/s). We observe in Figures 5 and 6 that in both cases (i.e., with and without collision detection), uplink throughput decreases as the number of mobile devices is increased. As the number of mobile devices is increased, fewer packets are successfully transmitted in the uplink, and therefore the throughput in the uplink declines. Comparing Figure 5 and Figure 6, we see that the uplink throughput is improved with collision detection.

Figure 7 merges the results from Figure 5 (dashed lines) and Figure 6 (solid lines) and clearly shows the improvement due to collision detection. Furthermore, this figure shows also the throughput if there is only minimal downlink traffic (top line).

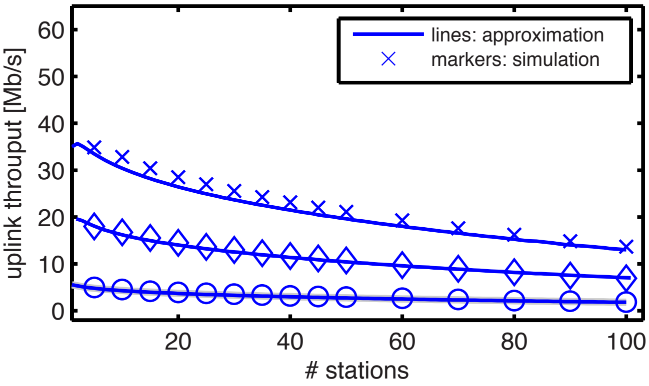


Fig. 5. Uplink system saturation throughput for 2x20 MHz, max data rates= 54 Mb/s, 24 Mb/s, 6 Mb/s. No collision detection. Larger device numbers are included in the evaluation since TVWS targets large coverage areas with large numbers of associated devices per access point.

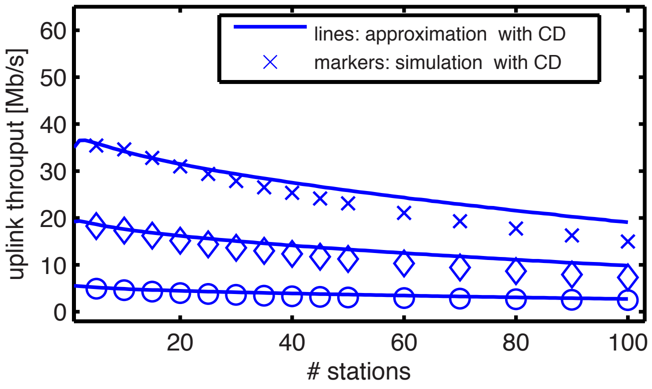


Fig. 6. Uplink system saturation throughput for 2x20 MHz, max data rates=54 Mb/s, 24 Mb/s, 6 Mb/s. With collision detection (CD).

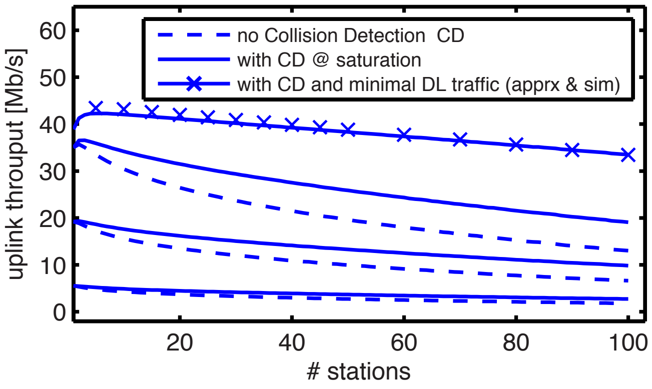


Fig. 7. Comparison and expected gain of uplink collision detection. In addition, maximum gain for times with minimal downlink is shown.

As the number of devices increases, we observe a slight reduction in throughput even in this case. This reduction indicates that even with notification upon detection of a collision, there is still a small loss of link bandwidth due to collisions. As downlink traffic is increased (as in any realistic scenario), the base station forfeits the opportunity to send a notification and therefore we see clearly that the uplink throughput decreases as we increase the number of mobile devices. Therefore collision detection can make a contribution to the uplink throughput.

VII. CONCLUSIONS

In this paper, we present an 802.11-like contention-based protocol operating in paired spectrum. The proposed protocol utilizes the Carrier Sense Multiple Access (CSMA) technique to take advantage of an additional channel in paired spectrum. Extensive event driven simulation results support that the proposed protocol can function efficiently in paired spectrum.

With the protocol described here, communication in paired spectrum becomes more feasible, using a low cost 802.11-like non-centralized random access scheme, in scenarios of cellular networks, or for the TVWS. As the dedicated licensed spectrum becomes more and more crowded, we expect that the basic protocol extension presented here will provide a foundation for many cost-effective approaches to dual-spectrum communication.

ACKNOWLEDGEMENT

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